NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

# TECHNICAL REPORT

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## BREAKDOWN OF PRESERVATIVE FLUID MIL-PRF-46170 IN AIRCRAFT HYDRAULIC SYSTEMS

by

Jeffrey W. Moorman

29 March 2001

DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
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14. ABSTRACT

This document summarized a series of laboratory tests performed to identify material forming on hydraulic system filters of fleet aircraft. Additional information obtained from outside sources is also summarized for background. Laboratory pump testing showed rapid filter clogging with small amounts of preservative fluid (MIL-PRF-46170) in the system. Similar conditions with 100% hydraulic fluid (MIL-PRF-83282) did not clog filters at these rates. Preservative fluid at elevated temperatures showed breakdown, increase in acid number, and chemical attack of test coupons while hydraulic fluid alone does not degrade. Preservative fluid is not compatible with operating aircraft hydraulic systems.

15. SUBJECT TERMS

| | | | | | |
|---|---|---|---|---|---|
| Preservative Fluid | MIL-PRF-46170 | MIL-H-46170 | Filter Clogging | Filter Plaque | Fluid Breakdown |
| Hydraulic Fluid | Sediment | Copper Clelate | Insoluble | Organic Gel | MIL-H-23699 |
| MIL-PRF-23699 | Copper | Bronze | Premature Wear | Corrosion | Acid |
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## SUMMARY

Several programs have experienced problems associated with breakdown of preservative fluid in aircraft hydraulic systems. This report documents differences between hydraulic fluid and preservative fluid with regard to fluid breakdown, component damage, sediment formation, filter clogging, and component malfunction.

Hydraulic fluids can be damaged under operational conditions. The rate of fluid breakdown generally increases with increasing temperatures. A catalyst is defined as an active substance that increases the rate of reaction at a given temperature. Similarly, a catalyst can reduce the temperature threshold for given reaction to occur. The Design Guide for Military Applications of Hydraulic Fluids (MIL-HDBK-118) identifies air and water contamination and the presence of metallic particles, dirt, and dust as catalysts promoting fluid oxidation.

Preservative fluid (MIL-PRF-46170) is a super-saturated 2% solution of a corrosion inhibitor additive, Barium Dinonylnaphthalene Sulfonate (BSN), in a base stock of hydraulic fluid (MIL-PRF-83282). This additive tends to leave the fluid and adsorb onto metal surfaces, forming a closely packed hydrophobic monomolecular protective barrier between the fluid and active metal surfaces. In some fluid systems, this additive type is known as a passivator because it converts active catalytic surfaces to passive surfaces, which no longer promote fluid breakdown.

In laboratory tests, elevated temperatures caused breakdown of preservative fluid, formation of acids, and damage to metal surfaces. Hydraulic fluid samples under the same conditions showed no evidence of degradation. Testing in a laboratory pump loop with 5% preservative fluid resulted in fluid breakdown and rapid filter clogging. Hydraulic fluid in the same pump loop under the same conditions showed no evidence of fluid breakdown or filter clogging.

Hydraulic filter elements from F-14 and F/A-18 fleet aircraft, with hydraulic fluid and small amounts of preservative fluid, are prematurely clogged with an insoluble organic gel (plaque). Filter elements from V-22 hydraulic systems (no preservative used) are in service much longer and a clogged filter showed wear material but no organic plaque buildup.

Except for hydraulic pumps, all steel components for aircraft systems in contact with hydraulic fluid have a minimum of 12% chromium. Inspection of a postcrash V-22 hydraulic pump stored in excess of 6 years with residual system fluid showed no evidence of storage related corrosion, and all components were within overhaul limits. Additional storage tests of two F/A-18E/F pumps stored for 9 months with hydraulic fluid with 375 and 500 ppm water contamination showed no evidence of storage related corrosion. Foreign military programs have never used preservative fluid and report no hydraulic system corrosion problems.

While preservative fluid was intended to provide additional corrosion protection under harsh storage conditions, several programs have identified in-service preservative fluid breakdown, causing component damage and uncommanded flight control problems. Preservative fluid is not compatible with conditions inside operating aircraft hydraulic systems and should be eliminated to prevent damage to aircraft hydraulic systems.

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# SECTION 1
# PROBLEM DESCRIPTION

## GENERAL

Hydraulic filters from several U.S. Navy aircraft are clogging prematurely. Filter elements are loading with insoluble organic material (filter plaque) instead of metal particles and wear debris as expected. Fluid breakdown is suspected since the amount of material far exceeds the amount of wear debris from system components.

While primarily organic, analysis of the filter plaque identified unusual amounts of barium and sulfur. The only known source of barium in the hydraulic system is the preservative additive in MIL-PRF-46170. This additive, Barium Dinonylnaphthalene Sulfonate (BSN), has proven unstable at elevated temperature and has been linked to component damage, filter clogging, sediment, and sticking valves.

Preservative fluid (MIL-PRF-46170) is a super-saturated 2% solution of a corrosion inhibitor additive, BSN, in a base stock of (MIL-PRF-83282) hydraulic fluid. The solubility for this additive is very low and most of the BSN tends to leave the fluid and adsorb on metal surfaces to form a closely packed hydrophobic monomolecular protective film. This protective barrier prevents the surface from direct contact with fluid-borne water and thereby prevents surface corrosion.

Wear or abrasion can rupture the adsorbed protective film and leave surfaces vulnerable to corrosion. The barrier can be repaired with time if there is sufficient fluid-borne preservative additive. Large amounts of water contamination may also result in damage to the protective film or leaching of the preservative additive from the fluid.

BSN is produced by heating a mixture of alcohols and acids in contact with an active catalyst (copper) surface. Water is a byproduct of this reaction. BSN is very stable in a laboratory environment, but several aircraft programs have observed in-service breakdown of preservative fluid. It is suspected that conditions within operating hydraulic systems (water contamination and extreme surface temperatures of copper components) may cause a small portion of the BSN to split into its original acids and alcohols.

The acids cause corrosion of internal surfaces. The products of corrosion are typically insoluble gelatinous compounds or dissolved metal ions. The metal ions promote oxidation damage of the fluid and formation of additional acids, each reaction a catalyst for the other. In this environment, the resulting acids can rapidly damage surfaces, form insoluble gelatinous products of corrosion, and clog system filter elements while leaving bulk fluid properties unchanged.

## HISTORY OF PROBLEMS WITH PRESERVATIVE FLUID

U.S. Army M-1 tank hydraulic systems use preservative fluid as an operating fluid and system heat exchangers are sized to maintain low operating temperatures. Parker/Abex engineers report severe corrosion damage to pumps from systems that overheated in service. Similarly, Vickers experienced problems qualifying the M-1 tank hydraulic pump (PV3-205-38D) at elevated temperatures. Bronze internal surfaces of the pump were eaten away by acids produced and copper was plated throughout the test stand. Each successive pump failed faster than the previous and the problem continued to escalate. Emptying the stand and filling with 100% hydraulic fluid eliminated damage and allowed the pump to complete high temperature endurance testing.

U.S Army M-60A1 tanks experienced problems with stuck/inoperative servovalves in the gun control systems of the M-60A1 tank. A task force report (ADA066581 dated July 1978) concluded that trace amounts of polypropylene glycol in one vendors fluid, in the presence of adsorbed water, caused precipitation of the rust inhibitor on critical surfaces of spool valve systems.

U.S. Air Force in 1986, while investigating T-38 Talon uncommanded flight control incidents (SWI Project Number 06-8295), experienced rapid filter clogging and sediment formation at elevated temperatures with one particular fluid sample. The sediment was high in barium and sulfur. One fluid supplier had inadvertently shipped hydraulic fluid with high levels of preservative additive. Other fluid samples tested under these conditions did not form sediment or experience filter clogging. At that time, there were no limits on the amount of preservative fluid within as-delivered hydraulic fluids. Recently, the specification for MIL-PRF-83282 hydraulic fluid was revised to set maximum limits for the preservative additive in new hydraulic fluid.

U.S. Army UH-1 helicopters experienced a sudden increase in problems with sticking valves (HR Textron Document No. HR 73200346). Problem was traced to in-service breakdown of residual preservative fluid. Maintainers stopped draining actuators prior to installation of components, causing fluid-borne preservative levels to increase with time. In-service breakdown of preservative additive in systems formed insoluble sticky material inside hydraulic valves and eventually caused valves to malfunction. Cleaning the valves with toluene/xylene and minimizing levels of preservative additive in system fluid for these systems has eliminated this problem for the past several years.

The CH-47 Chinook helicopter uses a dual concentric servovalve to protect against binding of the primary spool valve for the upper boost actuator for rotor control. The primary spool is sized for full flow and used for all normal flight conditions. Any binding of the primary spool will actuate the secondary spool and set a failure indication. Unfortunately, several aircraft have experienced binding of the secondary spool (latent failure of backup system) followed by binding of the primary spool, resulting in uncommanded flight control events.

A recent accident investigation identified clear organic deposits on servovalve sliding surfaces of the CH-47 rotor system upper boost actuator. Previous inspections had focused on witness marks and mechanical deformation of valve surfaces. The material was high in barium and sulfur and

believed due to in-service breakdown of the preservative fluid additive. On 22 February 1999, CDRAMCOM Redstone Arsenal AL/AMSAM-SF-A issued CH-47-ASAM-02, which directs servicing of test stands for CH-47 flight controls and utility systems with MIL-PRF-83282 to reduce high levels of preservative in system components. Controlling the level of preservative in system fluid has reduced the number of actuator problems during the past year.

## PROBLEMS WITH FILTER CLOGGING

This section contains a summary of problems with premature filter clogging. Additional details and pictures of filter media are included in the appendix section of this report.

Filter elements for F-14 hydraulic systems are replaced every 300 hr phase inspection or with delta pressure indicator showing. Inspection of a prematurely clogged filter element revealed large amounts of red organic material collecting within the filter media. Many of the smaller fluid passages through the media were blocked with an insoluble red organic gel.

The F/A-18C/D hydraulic system heat exchanger is easily overwhelmed by sustained flight control activity and system components show evidence of high fluid temperatures. All filter elements are replaced at 200 hr or on indication. Filter elements are loaded with an insoluble dark green organic gel. Recently, the F/A-18C/D community has also reported several problems with a light green organic material that discolors standard 0.5 micron filter patches.

Late in the Engineering Manufacturing Development (EMD) phase of F/A-18E/F flight test effort (shortly after introduction of a larger pump), operators started to report rapid filter clogging. The filter elements were coated with an insoluble dark green organic gel. Filters continued to clog at ever increasing rates until some filters were clogged at 20 flight-hours. During the same time, the leading edge flap hydraulic drive unit (HDU) motors started to experience premature wear. Each replacement motor failed faster than the last. A redesigned HDU motor has significantly improved motor life and also reduced the rate of plaque buildup in system filters. With the improved HDU motor, the filter plaque is red in color and similar to plaque forming on F-14 filter elements.

The V-22 program did not use preservative fluid during the short EMD phase of testing. System filters are common 5 micron elements used on F-14 and F/A-18 aircraft and are replaced only when delta pressure indicator is showing. One element on one aircraft was clogged at 200 flight-hours while all other elements are still in service with well over 500 flight-hours. The filter element showed wear debris as expected but, after washing with PD-680, filter fibers were clean and uniform with no evidence of filter plaque.

The integrated drive unit for the Boeing 777 standby generator uses MIL-PRF-23699 (a synthetic oil) as the working fluid. Customers experienced premature filter clogging that was much worse on brand new units. Analysis of clogged filters showed an insoluble green organic gel (copper chelate). Testing showed this material was a corrosion byproduct caused by in-service fluid breakdown.

Harsh conditions inside the generator drive unit were damaging a sensitive passivator additive, forming acids, and eating away internal surfaces. One of the products of corrosion was copper chelate (an insoluble green organic gel), which quickly loaded system filters. The filter vendor developed a second material that has helped protect the fluid from damage. Several military aircraft are using MIL-PRF-23699 for generator and Airframe Mounted Accessory Drive (AMAD) systems and are likely experiencing similar reliability problems. The system materials and products of corrosion for the generator are very similar to those found in military hydraulic systems.

## CAUSAL FACTORS AFFECTING FILTER CLOGGING

Early in the F/A-18E/F development effort, filter service life was as expected (200+ hours). Later, something within the system changed and filters started to clog prematurely at 70 flight-hours. Rate of filter clogging increased until some filters were clogged in less than 20 flight-hours. Recent hardware modifications have significantly reduced the buildup rate of filter plaque. Understanding the factors that caused this problem to come and go is critical to protecting systems.

Systems that experienced rapid filter clogging also had problems with premature wear of leading edge flap HDU motors. The smaller HS-1 system had more clogged filters and failed HDU motors than HS-2. As of 13 October 1999, 13 motors had failed on HS-1 systems and 6 had failed on HS-2. Of those failed motors, the average leakage growth rate was 4.21 gpm per 100 flight-hours on HS-1 and 2.08 gpm per 100 flight-hours on HS-2.

The HS-1 hydraulic system contains half as much fluid as the HS-2 system. With comparable flow rates, fluid in HS-1 system circulates twice as often. If fluid damage is cumulative, HS-1 would tend to accumulate twice as much damage as HS-2. This was consistent with filter service usage, which showed twice as many plugged filters on the smaller HS-1 system.

While related to motor failures, the filter plaque contained very little wear material and was primarily organic. The following factors appeared to affect the rate of filter clogging on F/A-18E/F hydraulic systems:

a. Elevated Fluid Temperatures – The original 56 gpm pump was determined inadequate for system demand and a larger 78 gpm pump was developed. The larger pump caused the hydraulic systems to operate warmer by 20 to 30°F. Filter clogging problems started shortly after the larger pump was introduced.

b. Active Metal Catalyst – The systems experiencing filter clogging also showed premature wearout of leading edge flap HDU motors. Motors in these systems were constantly exposing fresh wear surfaces. Copper is an active catalyst for chemical reactions and the unprotected metal surface reduces the temperature needed for a reaction to occur.

c. HDU Motor Cavitation – The F/A-18E/F HDU motor is identical left to right. To limit motor speed, restrictors were used to and from the motor. Unfortunately, with an aiding load condition, the restrictors cause cavitation of incoming fluid. This adds to fluid stress and causes significant local heating. Honeywell has identified cavitation-related damage inside returned HDU motors. This damage is not present in test stand motors.

d. Excessive Internal Leakage – The worn motors developed much higher internal leakage when compared to new motors. This added leakage caused local heating and elevated bulk fluid temperatures throughout the system.

e. Elevated Local Surface Temperatures – The worn leading edge flap motors had metal-to-metal contact with very high internal surface temperatures, which may have increased the rate of fluid breakdown.

f. Products of Fluid Breakdown – Breakdown of the preservative additive forms acids within the fluid. Coupled with extreme local temperatures, the acids can rapidly cause significant damage to internal surfaces. One motor with 4 flight-hours showed bronze from the cylinder liners had been transferred to the steel pistons. What looks like rapid wear is actually acid related corrosion of motor internal surfaces. Products of corrosion are typically insoluble organic gels and products of fluid breakdown are typically catalysts for further fluid breakdown (Design Guide for Military Applications of Hydraulic Fluids, MIL-HDBK-118).

g. Wear Particles – Hot fluid coupled with fine metal particles such as copper, from bronze or brass parts, can be reactive with the air and water in the fluid, causing further generation of heat and fluid breakdown (SAE - AIR1922 System Integration Factors That Affect Pump Life). Since the finest filtration used is the 3 micron ground cart filter, the concentration of fine particulate in system fluid tends to increase with time.

The V-22 program does not require preservative fluid and the same filter elements last much longer in V-22 systems (400+ hours) and show no buildup of organic material.

The F/A-18E/F rapid filter clogging problems were caused by breakdown of the preservative additive forming acids within the fluid, dissolving the bronze cylinder liners inside the HDU motor and exposing fresh copper. The fresh copper surface accelerated fluid breakdown and both reactions built on each other until filters were clogged with dark green plaque and motors were worn out after 30 hr. The redesigned HDU motor is performing much better in service and appears to have also corrected problems with premature filter clogging.

While the rate of filter clogging has been significantly reduced, filter elements now show gradual formation of an insoluble red organic gel, similar to F-14 system filters. This material is generated by in-service fluid breakdown and can only be resolved by eliminating preservative fluid from hydraulic systems.

## ANALYSIS OF CLOGGED AIRCRAFT FILTER MEDIA

Filter elements removed from F/A-18E/F hydraulic systems show a media coated with carbon soot, hydraulic fluid, and fine wear particles (silt). Filter vendor found 93% of material washed from filter was organic (Pall SLS Report No. 7510). Carbon soot is very fine (less than 1 micron in size) and consistent with fluid breakdown, which chemically forms microscopic particles within the fluid. Wear material and pieces of O-ring are typically much larger in size. Wear particles smaller than 5 microns in size typically pass through filter media so the level of silt in system fluid tends to increase with time.

Rinsing the filter media with PD-680 to mechanically remove the loose upper layer reveals a bottom layer of green/brown insoluble gelatinous material (filter plaque). This organic gel adheres to filter fibers, traps wear particles, and blocks flow passages through the media. The filter plaque can only be dissolved with a polar solvent (such as toluene/xylene or hexane). Fluid breakdown is suspected since the amount of organic material in the filter far outweighs amounts of system organic wear debris. Washing the media with toluene/xylene dissolved the plaque and resulted in clean filter fibers. After evaporating organic components from the solvent wash fluid, Proton Induced X-ray Emission analysis showed up to 17% by weight barium (Pall SLS Report No. 7900). The continued presence of barium and sulfur in filter plaque and wash fluid identify breakdown of preservative additive BSN.

## SUMMARY OF PROBLEMS

The preservative additive in MIL-PRF-46170 is not compatible with operating conditions inside aircraft hydraulic systems and can break down in service to form harmful acids within the fluid. These acids can rapidly eat away at component internal surfaces, forming sediments and insoluble products of corrosion, which prematurely clog system filters. Several programs have experienced problems with breakdown of preservative fluid and actively reduced levels of preservative fluid in system hydraulic fluid. Hydraulic fluid alone is not affected by these conditions.

Many aircraft in Navy inventory experience problems with formation of insoluble gelatinous material and premature clogging of system filters. Filter clogging problems on F/A-18E/F have been linked to in-service breakdown of residual preservative fluid by continued presence of barium and sulfur. Filter clogging problems increased significantly due to one of several factors late in EMD flight testing. Redesign of the HDU motor has resolved premature wear and dramatically reduced the rate of filter clogging.

Preservative free V-22 filter elements show no accumulation of filter plaque or insoluble material and filters are still in service after 500 hr.

## SECTION 2
## HYPOTHESIS

Preservative fluid is not compatible with high operating temperatures inside aircraft hydraulic systems. The preservative additive (BSN) can break down in service and form acids within the fluid. These acids can damage system components and form insoluble products of corrosion such as sediments and organic gels, which quickly load system filters. Hydraulic fluid is able to withstand these conditions without damage.

The rate of filter clogging varies widely from system to system. Several factors such as fluid temperature, fluid volume, water contamination, and active metal surfaces are likely affecting rate of fluid breakdown. The correct combination of environmental factors within a laboratory pump loop should be able to duplicate the aircraft filter clogging problem.

Hydraulic fluid (MIL-PRF-83282) provides sufficient corrosion protection for storage of aircraft hydraulic system components. All steel components in contact with hydraulic fluid require a minimum of 12% chromium in the alloy. This requirement is waived for hydraulic pumps to meet endurance and strength requirements. Hydraulic pumps are therefore the most corrosion prone components in aircraft hydraulic systems. Pump storage tests with water contaminated hydraulic fluid can be used to evaluate the corrosion protection provided in adverse storage environments. If long-term storage of hydraulic pumps in hydraulic fluid does not produce corrosion damage, other system components should also be adequately protected.

# SECTION 3
# LABORATORY FLUID TESTING

## THERMAL STABILITY TESTING

Accelerated corrosion testing is part of the qualification testing for both hydraulic fluid and preservative fluid. Test metal coupons are submerged in the test fluid, which is then heated to 250°F for 168 hr per ASTM D-4636. This testing (performed by Petro-Lubricant Testing Laboratories, Inc., 23 November 1999) was intended to evaluate fluid breakdown and damage to metal test coupons at elevated temperatures.

Testing with hydraulic fluid at 250°F showed no acid formation or damage to metal test coupons. The qualification test allows some material loss and acid formation but, fluid without preservative, shows no evidence of degradation.

Preservative fluid testing showed evidence of soot formation, change in fluid acid number, and caused measurable weight loss to metal coupons. At 250°F, the coupon damage and acid formation (0.39 mg KOH/g) were beyond qualification limit of 0.20 mg KOH/g. At 225°F, the fluid damage was less severe (0.12 mg KOH/g) and within allowable limits for the fluid.

Summary: Hydraulic fluid was able to withstand elevated temperatures without fluid breakdown or damage to metal test coupons. Preservative fluid under the same conditions showed evidence of breakdown and caused measurable damage to metal test coupons.

## FLUID BOMB TESTING

Two samples of HDU rotor were sealed and heated to 500°F in an oven for 12 hr at the Allied Signal facility in South Bend, Indiana. One sample was covered with 100% hydraulic fluid (MIL-PRF-83282); the other sample was covered with 100% preservative fluid (MIL-PRF-46170). This testing was performed on 3 May 1999 to quantify suspected damage to HDU motor bronze surfaces at elevated local temperatures.

The rotor sample in hydraulic fluid contained clear, amber fluid, indicating damage to the coloring agent at higher temperatures. The fluid was clean with no visible particulate and no visible damage to metal surfaces (bronze or steel).

The rotor sample in preservative fluid showed visible coking of the fluid and formation of carbon soot. The fluid was black with large quantities of visible particulate. The bronze test sample was severely damaged with a significant amount of the bronze material eaten away. The steel surface had been coated with an insoluble black material.

Results: Hydraulic fluid was able to protect the rotor surface during these test conditions without damage to fluid or metal surfaces. Preservative fluid under the same conditions showed breakdown and coking of the fluid with significant weight loss and etching of the bronze surface.

## FALEX WEAR TESTING

Several falex wear test specimens were tested at the Allied Signal facility in South Bend, Indiana, on 3 May 1999. The machined specimens of various metals were loaded in a fixed repeatable manner and lubricated with a specific fluid. This test was a quick check for incompatible wear metals or lubricants. Temperature of the fluid was maintained at 200°F throughout testing.

Steel against bronze lubricated with preservative fluid showed severe damage with a wear scar 6.5 microns in depth and stalled the test machine at 77 min. The duration of the falex test was planned for 90 min, but the falex machine stalled under the severe wear and increased torque load.

Steel against bronze lubricated with hydraulic fluid under the same conditions showed polishing and minimal wear (0.64 microns in depth) after 77 min. This was less than 10% of the depth for the falex specimen lubricated with preservative fluid for the same conditions.

Results: Falex testing indicated preservative fluid caused additional damage or did not protect the specimen as well as hydraulic fluid during these operational conditions.

## THERMAL BREAKDOWN OF PRESERVATIVE ADDITIVE

The Materials Engineering Laboratory at NADEP Jacksonville performed several tests to investigate thermal stability of the preservative additive in MIL-PRF-46170 (Report Number 99JX01805) with the following results.

Products of thermal breakdown caused large acid number increases and promoted oxidation of base MIL-PRF-83282 fluid. Rate of fluid degradation was not dependent on amount of copper present. Acid formed within the fluid caused significant damage to copper test coupons.

Above 212°F, the preservative additive starts decomposing and forming visible soot and acids within the fluid. Hydraulic fluid (MIL-PRF-83282) is stable to 400°F with minimal acid change and no visible particulate. Preservative fluid should never be present in any system where fluid temperatures exceed 212°F. It is important that this fluid be drained and purged from any component before installed in an aircraft hydraulic system.

# SECTION 4
# OPERATIONAL PUMP LOOP TESTING

## DESCRIPTION OF PUMP LOOP HARDWARE

A series of tests was performed to investigate the factors affecting the aircraft hydraulic system filter clogging problem in a controlled environment. Several conditions in the pump loop were adjusted to study the effects on filter clogging rate.

A laboratory pump loop was built with a hydraulic pump and reservoir from an F/A-18C/D aircraft. The pump was operated at 3400 rpm and loop flow rate was alternated between 10 to 20 gpm every 30 sec. Total system volume was 10 gal for phase 1 testing. Later testing was performed with a reduced system volume of 5 gal to more accurately simulate the HS-1 aircraft hydraulic system. A water-cooled heat exchanger was used to maintain return fluid temperature.

Pressure gauges and thermocouples were used to monitor system performance at several locations in the system (pump inlet, pressure, and case drain). The pump loop included two 5 micron filters, one at the discharge of the pump and the other in the case drain circuit. A return filter was not needed since there were no actuators in the system. Temperature and pressure values were logged every 30 min during testing.

## PUMP LOOP TESTING - PHASE 1

System return temperature was maintained at 235°F and clean filter elements (18 psi delta) were used for each test.

Test 1 - (8 hr) with 1 gal of preservative fluid in a 10 gal system resulting a pretest fluid level of 230 ppm barium. After this test, the filters were severely plugged and fluid barium level was reduced to 130 ppm barium. Analysis of clogged filters revealed a large amount of grit. Unfortunately, some residual sand had been missed in the setup process and the filter was plugged with a mixture of organic material and sand. There was a noticeable green cast to the material in the filter bowl.

Test 2 - (5 hr) starting with 130 ppm barium and a clean system. After this test, the fluid measured 89 ppm barium (significant reduction in fluid barium content) and filters showed a delta of 58 psi delta (2/3 loaded) in 5 hr. There was no sand or grit in the filter bowl but the filter loading rate was still very high.

Test 3 - (5 hr) after flushing and filling system with clean hydraulic fluid. After this test, the fluid sample measured 1 ppm barium and filter showed 28 psi delta in 5 hr (a buildup of only 10 psi after 5 hr, which was much less than during previous testing).

Test 4 - (5 hr) a second cleanup run with 22 psi delta (4 psi additional buildup in 5 hr).

Test 5 - (5 hr) a third cleanup run with 20 psi delta (2 psi additional buildup in 5 hr).

Test 6 - (5 hr) after adding 1 qt of preservative fluid to 10 gal of system fluid. Filters showed 18 psi delta in 5 hr (no buildup).

Test 7 - (5 hr) after adding a second quart of preservative fluid and filters showed 18 psi delta (again, no buildup).

Test 8 - (5 hr) after adding two additional quarts of preservative fluid. Filters again showed 18 psi delta (no buildup).

Test 9 - (2 hr) after adding bronze shavings to filter bowl, 18 psi delta (no buildup).

Test 10 - (2 hr) after adding 100 ppm water contamination, 18 psi with no additional buildup.

Test 10+ (15 min) with all previous contaminates plus a pinch of sand in the pump inlet hose to create fresh wear surfaces inside the pump. The system started normally with stable pressures and temperature started to climb. As temperature reached 200°F, the pump started making strange sounds. The gauges looked acceptable except for case drain pressure, which was rapidly climbing, which typically indicates a failing pump. The pump was secured to avoid further damage.

Results: The case drain fluid was black and the filter was loaded with soot. Analysis of filter debris showed carbon chunks primarily 10 to 25 micron in size. Teardown inspection of the pump showed no obvious signs of internal damage or elevated temperatures. Pump was reassembled and the same pump was used for all additional testing. Some temporary condition within the pump produced a steady stream of soot in the case drain line and plugged the filter in 30 sec.

Test 11 - (3 hr) after pump was reassembled and system was flushed and filled with hydraulic fluid. System fluid measured 26 ppm barium and filter developed 28 psi (10 psi additional in 3 hr).

Test 12 - (3 hr) for a second cleanup run. System fluid measured 8 ppm barium and filter developed 22 psi (4 psi additional in 3 hr).

Test 13 - (3 hr) with same filter from test 12 and a pinch of sand in the pump inlet. Filter measured 25 psi (3 psi additional in 3 additional hours).

Results and Conclusions:

Rapid filter clogging was intermittent and the rate appeared related to concentration of preservative additive in system fluid.

Filter clogging, when present, significantly reduced concentration of barium in system fluid.

Preservative fluid alone was not sufficient to cause rapid filter clogging. Adding significant amounts of preservative fluid and other contaminants to system had no effect on filter loading during tests 6 through 10.

Presence of grit in system appears related to rapid filter clogging. The amount of sand present was not sufficient to load filters and sand is quickly captured by system filters, and therefore not present throughout testing.

Test 2, without sand, showed significant filter clogging, possibly due to fresh wear scratches within pump created during test 1.

Fresh bronze shavings added to filter bowl in test 9 had no effect on filter clogging. Sand in the system during test 13 with hydraulic fluid alone had no effect on filter clogging.

It appears that filter clogging requires preservative fluid in the system and fresh wear scratches inside the pump where surface temperatures are much higher than bulk fluid temperatures.

## PUMP LOOP TESTING - PHASE 2

System fluid volume was reduced to 5 gal to increase the rate of fluid damage and more accurately simulate HS-1 aircraft hydraulic system volume. To investigate steady state long-term filter loading rates, a new filter was left in the system for several successive days of operation.

Return fluid temperature was maintained at 215°F and filter pressure differential was measured at the end of each day of testing. Aircraft representative fluid chemistry caused steady long-term buildup of material in system filter (figure 1). Similar to aircraft filters, test stand filters were plugged with organic material collecting in 22 hr. This relatively long-term continuous buildup was evaluated in phase 2 testing.

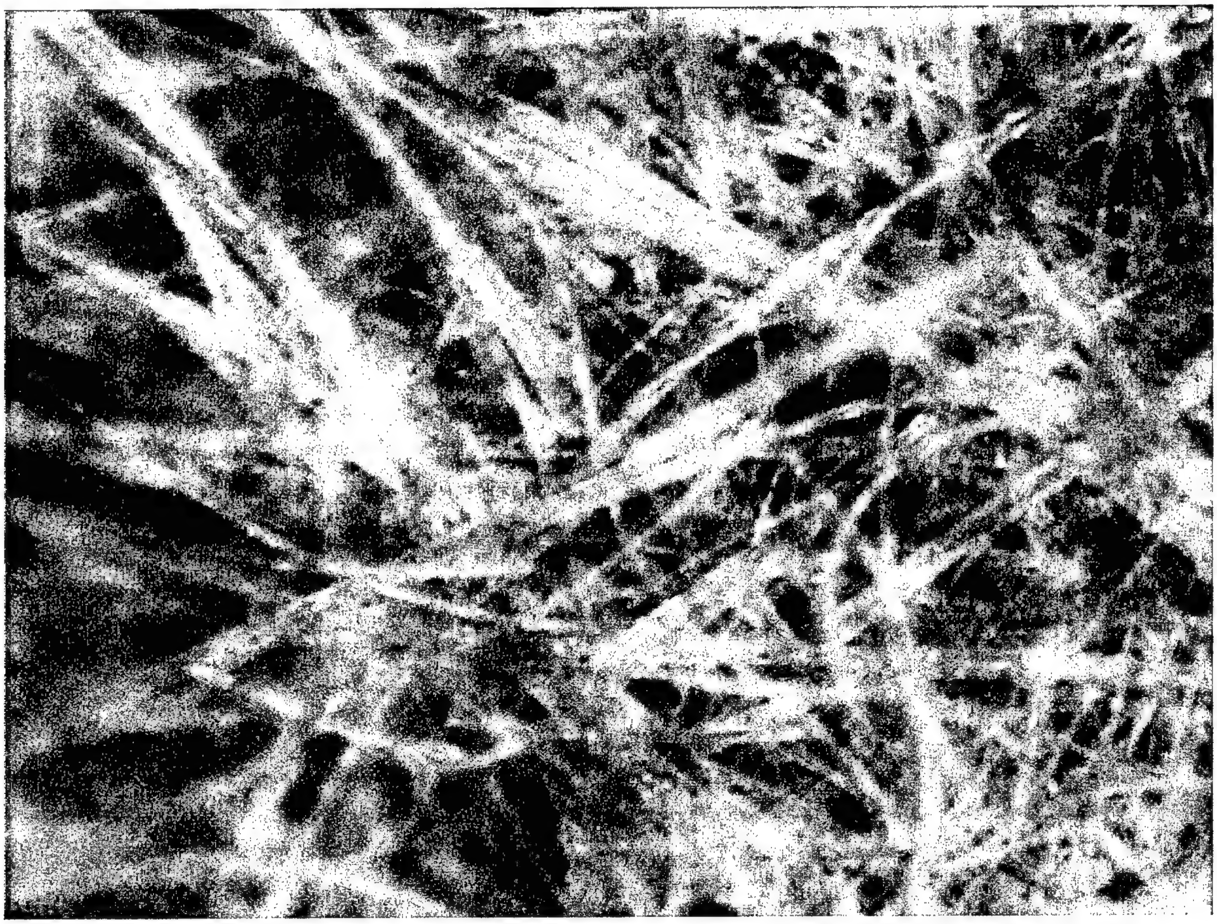

**Figure 1: Test Stand Filter Element After 22 hr**

## PUMP LOOP TESTING – PHASE 3

To quantify the effects of steady state long-term filter loading rates, a new filter was left in the system for several successive days of operation. At the end of each day testing, a fluid sample was collected and the filter pressure differential was measured.

Fluid temperature was maintained at 215°F and the first 2 days of testing were performed without preservative fluid to ensure a clean system. Filter loading for the first 2 days was minimal. Note that fluid barium level was reduced from 13 ppm to 0 ppm in the first 16 hr of testing as residual preservative was removed from system fluid.

The beginning of the third day, 1 qt of preservative fluid was added after 16 hr of operation (shown in figure 2). The rate of filter loading significantly increased after adding the preservative fluid. The level of residual preservative in fluid was steadily reduced as organic material was collecting on the filter.

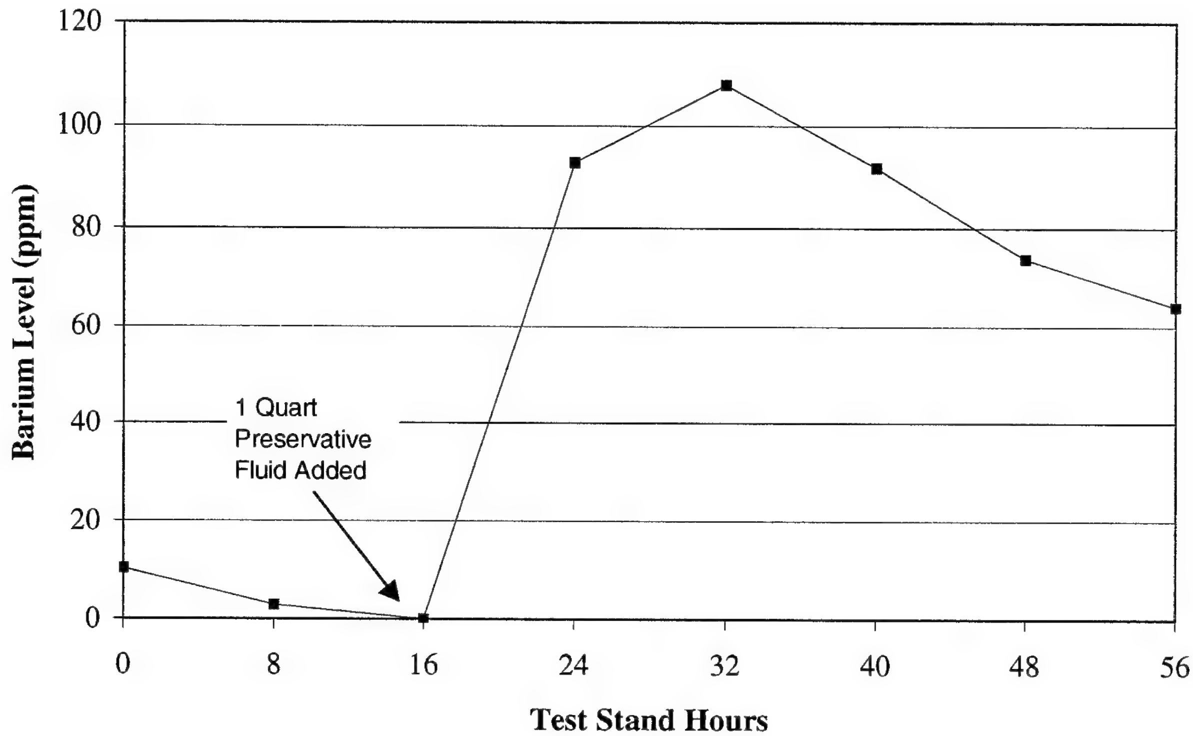


**Figure 2: Fluid Barium Level Versus Time**

Additionally, baseline testing was performed with 100% hydraulic fluid to quantify the effects of preservative on filter clogging. Baseline testing with low levels of preservative showed minimal filter loading for the first 45 hr of testing (figure 3).

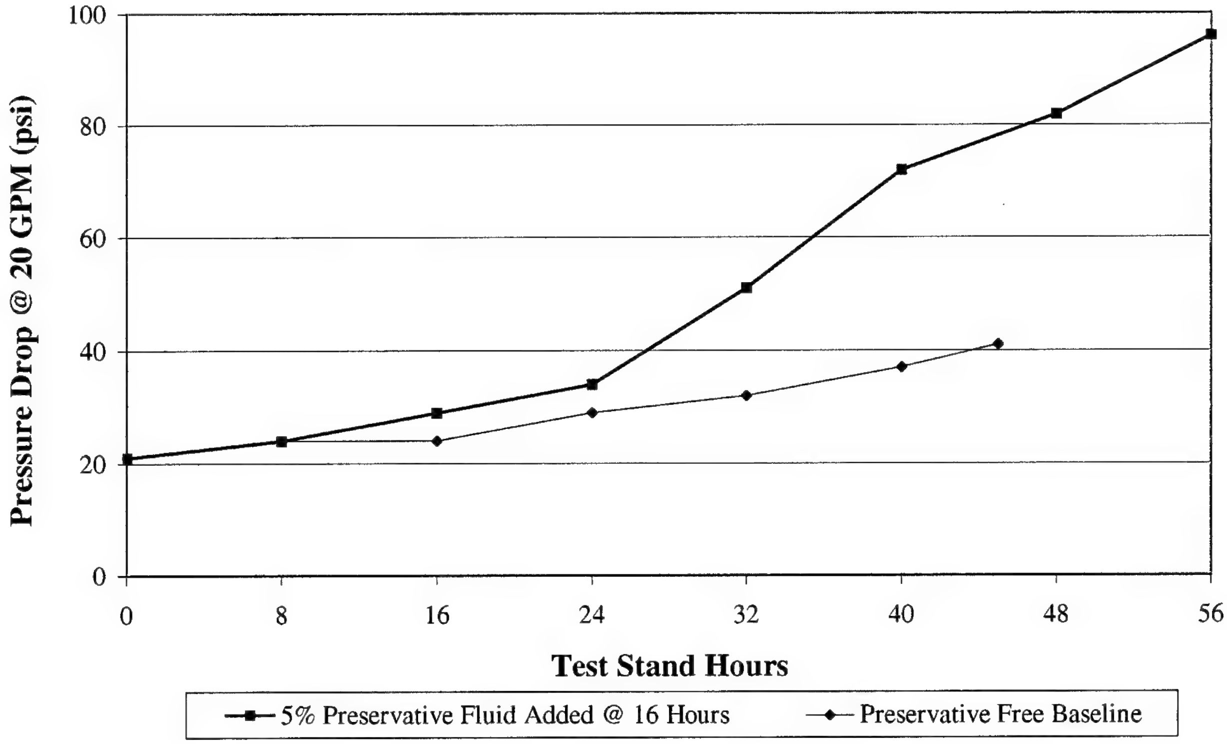


Figure 3: Filter Element Pressure Drop Versus Time

System baseline testing had progressed to 45 hr with minimal filter loading when an abrupt increase in pressure was observed. Inspection of the system identified a rupture in the heat exchanger that was adding large amounts of water to system fluid.

Inspection of filter media showed that material was present in large chunks against relatively clean media fibers (figure 4). The ruptured heat exchanger allowed water (a polar solvent) to enter the system and release large chunks of material that had formed in the system during previous testing or was an agent causing extremely rapid fluid breakdown under these conditions.

In either case, since system water levels were well in excess of allowable water levels in the field and system conditions were correct during the first 45 hr of baseline, earlier test data are considered valid. Minimal loading of system filters was produced during the 45 hr of baseline testing with little or no preservative fluid in the system.

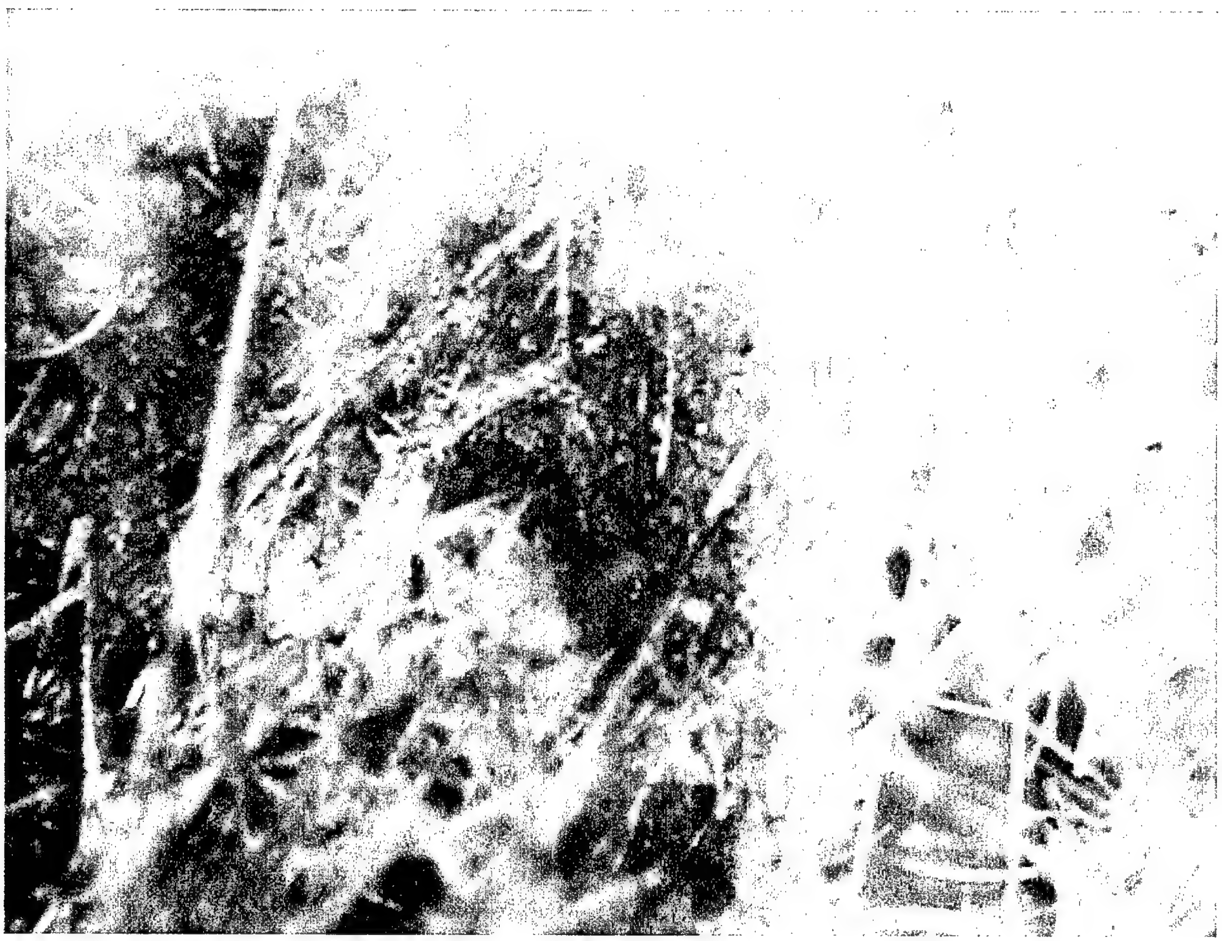

**Figure 4: Test Stand Filter Element (48 hr)**

## SUMMARY OF TEST RESULTS

Rapid filter clogging was intermittent. Rate of filter clogging appeared related to level of preservative in system fluid and the presence of fresh wear surfaces inside the pump.

Grit and fresh metal surfaces had no effect on filter clogging with hydraulic fluid alone.

Adding 1 qt of preservative fluid caused a significant increase in the long-term filter loading rate.

Hydraulic fluid baseline testing showed very little filter loading until the system heat exchanger ruptured. Water contamination caused rapid buildup of material on the filter even with minimal levels of preservative in the fluid. This may have been due to material collected on walls of the test stand during previous testing.

Visual inspection identified no permanent damage to the pump. The same pump was used for all three phases of pump testing.

# SECTION 5
# CORROSION PROTECTION

## HYDRAULIC FLUID AND CORROSION PROTECTION

Except for hydraulic pumps, all steel components for aircraft systems in contact with hydraulic fluid have a minimum of 12% chromium. Pumps require high strength alloys in addition to other corrosion resistant materials. Inspection of a pump stored for years with hydraulic fluid alone should verify that hydraulic fluid provides sufficient protection. Conversely, any storage related corrosion problems would indicate hydraulic fluid does not provide adequate corrosion protection. Preservative fluid experiences significant loss of ability to inhibit corrosion after 6 months due to precipitation of inhibitor additive (MIL-HDBK-118, Design Guide for Military Applications of Hydraulic Fluids).

## INSPECTION OF V-22 PUMP AFTER 18 MONTHS

A new V-22 hydraulic pump stored in original packaging for 18 months. Acceptance Test Procedures paperwork specified that the pump had been partly filled with preservative fluid. Fluid testing showed only 20 ppm barium. After 18 months, only a trace amount of the preservative additive remained in the fluid. All internal parts were within overhaul limits with no signs of storage related corrosion damage.

## INSPECTION OF V-22 PUMP AFTER 6 YEARS

A pump from a mishap V-22 was shipped with residual system fluid to NAWCAD Warminster. This pump was inspected as part of the mishap investigation and then stored for 6 years partially filled with residual system fluid from crash site. All internal parts were within overhaul limits with no signs of storage related corrosion damage.

## INSPECTION OF F/A-18E/F PUMPS WITH WATER CONTAMINATION

Two F/A-18E/F hydraulic pumps stored for 9 months half filled with hydraulic fluid contaminated with 338 and 573 ppm water, respectively. Even with excess water, there was no storage related corrosion damage identified in either pump.

## SHIPPING AND STORAGE OF U.S. NAVY HYDRAULIC COMPONENTS

Current U.S. Navy maintenance practice is to repair hydraulic components as required. All test stands are filled with MIL-H-46170 as per maintenance manuals. Components are tested, capped, wrapped, boxed, and shipped to supply system warehouses. Operational activities order components as required and are not allowed to stockpile extra components. Components are ordered as needed and unpackaged just prior to installation (several operational activities confirmed this practice).

With climate-controlled warehouses and current methods of packaging for shipment in the supply system, there is minimal risk of corrosion or storage related damage. Interviews with several operational units identified no incidence of internal corrosion. Damaged components returned to the rework facility have little if any residual system fluid and, even under these severe conditions, there have been no significant corrosion problems reported.

## EXPERIENCE OF FOREIGN MILITARY SALES COUNTRIES AND PRESERVATIVE FLUID

Foreign Military Sales (FMS) countries as a whole have not adopted preservative fluids (MIL-H-46170 or MIL-H-6083). System components are reworked, packaged, shipped, and stored in MIL-H-83282 hydraulic fluid. None of the FMS countries have reported component corrosion issues associated with lack of preservative fluid usage.

# SECTION 6
# CONCLUSIONS

## CONCLUSIONS FROM RELATED INVESTIGATIONS

1. M-1 tank pumps (Vickers PV3-205-38D) could not complete elevated temperature endurance testing with preservative fluid. Purging and filling test stand with hydraulic fluid eliminated severe internal damage and premature pump failures.

2. T-38 program laboratory testing developed sediment and clogged filters with one fluid sample with elevated levels of preservative additive. Other hydraulic fluid samples did not generate sediment or insoluble material under the same conditions.

3. UH-1 program identified insoluble organic material due to in-service breakdown of preservative fluid as the cause of flight control problems. Sampling and minimizing levels of preservative additive in system fluid has reduced the number of problems over the past several years.

4. CH-47 program identified insoluble organic gel on servovalves as part of uncommanded flight control investigation. Directing usage of MIL-PRF-83282 for component testing and storage and reducing levels of preservative fluid in systems has reduced the number of problems in the past year.

5. F/A-18E/F program identified preservative fluid as a contributor to leading edge flap motor failures and premature filter clogging. A recent material change has significantly reduced the rate of fluid breakdown and motor wearout, while increasing filter service life from 30 hr to well over 500 hr.

6. F/A-18C/D and F-14 aircraft show evidence of insoluble organic gel on system filters. Material is similar to plaque buildup on F/A-18E/F system filters and in-service preservative fluid breakdown is suspected.

7. Visual inspection of F-15 hydraulic system filters (green throughout) and reports of rapid wearout of hydraulic motors on F-16 aircraft suggest Air Force systems may also be affected by this problem.

8. V-22 hydraulic system filters (preservative-free system with no evidence of organic buildup) are still in service well over 500 hr, which is further evidence that this problem is not present on V-22 hydraulic systems.

9. Inspection of filters from constant speed drive units from S-3 and AV-8 aircraft electrical generators (other aircraft not inspected) shows products of corrosion similar to copper chelate found on Boeing 777 commercial aircraft generator integrated drive unit filters. This suggests similar in-service breakdown of MIL-H-23699 may be causing premature failures of AMAD and generator hardware.

## CONCLUSIONS RELATED TO LABORATORY TESTING

1. Elevated temperature causes breakdown of MIL-PRF-46170 preservative fluid forming acids and damaging metal coupons. MIL-PRF-83282 hydraulic fluid under the same conditions showed no signs of damage to fluid or metal coupons.

2. System fluid loaded with preservative fluid, water contamination, and bronze shavings did not experience rapid clogging and soot formation until grit was added to create fresh wear surfaces within pump.

3. Rapid test stand filter clogging was only present with system fluid above 200°F return fluid temperature.

4. Rate of filter clogging was related to level of preservative fluid in system fluid.

5. Rate of fluid breakdown (as with previous experience) was greater with water contamination, particulate, elevated temperatures, and fresh internal wear surfaces.

## CONCLUSIONS BASED ON COMPONENT STORAGE TESTING

1. There are no fleet reports of internal corrosion of hydraulic system components due to extended storage.

2. Existing supply system procedures create a relatively benign environment for hydraulic system components until they are installed on aircraft.

3. Even failed components shipped with little if any protection show no evidence of internal corrosion when received for rework.

4. FMS countries do not use preservative fluids and report no corrosion related problems (service or storage related).

5. V-22 pump stored in excess of 6 years with residual system fluid showed no evidence of storage related corrosion damage.

6. Even with significant water contamination, hydraulic fluid alone provides sufficient corrosion protection for long-term component storage.

# SECTION 7
# RECOMMENDATIONS

## RECOMMENDATIONS FOR CORRECTIVE ACTION

1. Identify hydraulic fluid MIL-PRF-83282 as the only fluid allowed for test, storage, and operation of U.S. Navy aircraft hydraulic system components.

2. Halt all future purchases of MIL-PRF-46170 for Navy aircraft hydraulic systems. MIL-PRF-83282 provides sufficient corrosion protection for component storage of hydraulic system components.

3. Direct all suppliers to test and fill U.S. Navy aircraft hydraulic system components with MIL-PRF-83282 prior to shipment.

Currently, all test stands supporting rework of hydraulic system components are filled with MIL-PRF-46170. Each component installed in a hydraulic system adds more preservative fluid to the system. Operating conditions break down the fluid, damage system components, and form byproducts of corrosion, which collect in system filters. A cleanup plan should address the following:

- Test Stands for Component Rework – Options range from complete drain and refill with MIL-PRF-83282 to attrition based solely on refill with MIL-PRF-83282. Since test stands currently have ~100% preservative fluid, to avoid prolonged cleanup duration, it is recommended to drain and refill test stands with MIL-PRF-83282. This will quickly halt the flow of MIL-PRF-46170 to field activities.

- Ground Support Equipment – Common service ground carts function as averaging devices for the systems supported. Draining these reservoirs will speed up the process but, since aircraft systems are heavily diluted (only ~2% preservative fluid), attrition is the preferred method to clean up ground servicing cart reservoirs.

- Aircraft Hydraulic Systems – Testing has shown that severe conditions are very quick to remove preservative from aircraft systems. If conditions in the system are not causing breakdown of aircraft fluid, then system fluid is acceptable. Attrition is recommended to address this problem for individual aircraft systems. Filter element changeout should correct this problem in a reasonable time frame.

- Components in Supply System – Due to the expense associated with reworking otherwise acceptable components and the lack of spare hardware in the supply system, attrition is also recommended to address this supply of preservative fluid. All components entering the supply system after a certain date shall contain MIL-PRF-83282.

## RECOMMENDATIONS FOR FURTHER STUDY

1. Investigate alternate fluids for constant speed drive (CSD) units and on U.S. Navy aircraft. There are several fluids that meet MIL-PRF-23699 requirements and some have increased stability at elevated temperatures.

2. Perform additional testing (if required) to support elimination of MIL-PRF-46170 requirements from U.S. Air Force hydraulic systems, as well. There is evidence to suggest in-service problems and eliminating a sensitive fluid reduces the risk of cross contamination throughout the industry.

# APPENDIX A
# LESSONS LEARNED ON SEVERAL AIRCRAFT HYDRAULIC SYSTEMS

## U.S. AIR FORCE EXPERIENCE WITH F-15 EAGLE HYDRAULIC SYSTEM

The F-15 uses a 46 gpm Parker/Abex hydraulic pump with a 1 1/4 in. pump inlet line and a 1 in. discharge line with a maximum inlet fluid velocity of 15 ft/sec. The pump is quick-change manifold design for easy replacement. The 3/8 in. case drain line is routed to the return filter and large heat exchangers are used to control system fluid temperature. Pump service life for the past several years has averaged between 3,000 to 6,000 hr.

The Air Force typically uses 15 micron filter elements for aircraft hydraulic systems vice 5 micron filter elements for Navy aircraft. F-15 hydraulic system filter elements are replaced every 600 hr. System reservoirs have integral temperature indicators that trip if fluid temperature exceeds 230°F (rare occurrence). The Air Force was not experiencing problems with hardening and cracking of actuator seals but upgraded hydraulic system seals for flight control actuators to improved Nitrile (MIL-PRF-83461) when Buna N was disallowed for design of new systems.

## U.S. AIR FORCE EXPERIENCE WITH F-16 FALCON HYDRAULIC SYSTEM

The F-16 uses 42 gpm hydraulic pumps with a 1 1/4 in. pump inlet line and a 1 in. discharge line with a maximum inlet fluid velocity of 14 ft/sec. The system reservoir has a bootstrap accumulator to maintain pressure during transient demands. While the accumulator will keep the system pressurized after shutoff, some maintainers manually relieve bootstrap pressure to prevent overnight fluid seepage.

F-16 hydraulic system uses 15 micron filters that are changed on condition only. Maintainers report several years of service between filter changes.

The F-16 engine uses a hydraulic motor driven fuel flow proportioning-pump. This F-16 hydraulic motor is similar in size to the F/A-18 HDU motor and has similar reliability problems with an average service life of 90 hr. Based on the F/A-18E/F HDU experience, a wrought bronze motor design for this motor would likely correct the premature wearout problem. The Air Force has directed maintenance depots to use low temperature hydraulic fluid (MIL-PRF-87257) for test and storage of components due to the history of in-service problems with preservative fluid (MIL-PRF-46170).

## U.S. NAVY EXPERIENCE WITH F-14 TOMCAT HYDRAULIC SYSTEM

The F-14 hydraulic pump produces 84 gpm with a full flow 1 1/2 in. inlet hose with a maximum fluid velocity of 18 ft/sec. The F-14 community has identified the damaging effects of air in hydraulic systems (action item 256A of 47$^{th}$ F-14 System Safety Review). Additional time spent purging air from hydraulic systems has paid off with increased component service life. This is especially critical for the backup flight control module in the tail of the aircraft. System temperatures are recorded via a temperature gauge on the filter manifolds.

Filter elements for F-14 hydraulic systems are replaced at each 300 hr phase inspection. Filters are also changed between phases if filter delta P buttons indicate excessive pressure drop. Filter elements for Navy aircraft trap particles 5 micron and larger in size. Inspection of a prematurely clogged filter element (shown in figure A-1) revealed large amounts of red organic material collecting within the filter media.

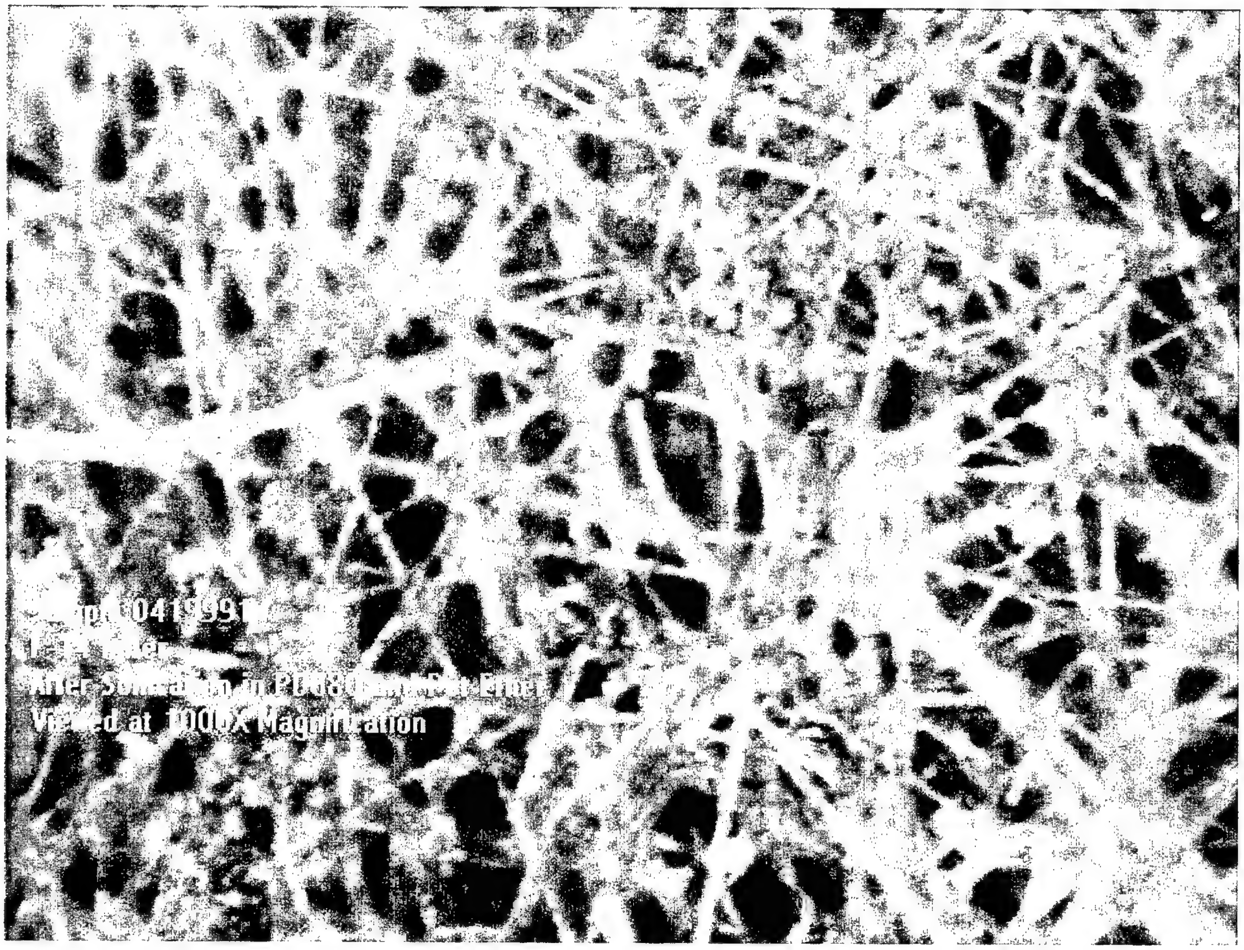

**Figure A-1: F-14 Filter Element After Wash**

The filter element was ultrasonically washed in PD-680 to remove hydraulic fluid and material mechanically trapped within the filter. While many of the larger passages are open, the smaller fluid passages through the media are blocked with an insoluble organic gel, causing a significant reduction in flow area and increased pressure drop. The filter plaque is red in color with a transparent gelatinous appearance. A polar solvent toluene/xylene is required to dissolve the filter plaque.

Over the past couple years, F-14 wingsweep motors have experienced premature wear. Typical motors require overhaul after 500 flight-hours and show evidence of high internal temperatures. Failed motors have broken pistons, severe shoe wear, and worn rotor bores. The latest (-20)

wingsweep motor with wrought bronze rotor showed little if any rotor wear during qualification testing. Based on F/A-18E/F experience, fielding this improved motor should also reduce the rate of plaque formation on system filters.

## U.S. NAVY EXPERIENCE WITH F/A-18C/D HORNET HYDRAULIC SYSTEM

The F/A-18C/D hydraulic system was developed with an emphasis on reduced weight. The pump is common to the F-15 (46 gpm) but uses smaller lines (1 in. inlet, 3/4 in. pressure, and 1/4 in. case drain). The AMAD gearbox drives the F/A-18 pump 20% faster than the F-15 gearbox to achieve a 56 gpm flow capacity but with a 36% reduction in flow area. This results in a theoretical inlet velocity of 29 ft/sec, which is higher than any other military hydraulic system.

This condition makes the system sensitive to air contamination and prone to transient cavitation and elevated fluid temperatures. Pump inlet pressure data show pressures oscillating between vacuum and 250 psi while responding to system demands. While not a steady state air lock condition, transient cavitation may cause increased fluid temperatures and reduced component reliability.

The system heat exchangers are small and easily overwhelmed by aggressive flight control activity. Components returned from F/A-18C/D hydraulic systems show evidence of excessive fluid temperatures and actuator reliability is well below expected levels throughout the system. Seals and electronic modules are heat damaged and components are discolored. Fifty percent of removals are due to hardened and heat damaged seals. Recently, maintenance depots switched from Buna N to improved Nitrile (MIL-PRF-83461) for overhaul of F/A-18 flight control actuators.

A McDonnell Douglas report (MDC A4576 dated 1977) showed a reduction in the F/A-18C/D pump case drain capability due to Newtonian fluid properties of MIL-H-83282 vice the original Non-Newtonian MIL-H-5606 fluid. Increasing back pressure reduces flow in the pump case drain circuit. With MIL-H-83282, the pump case drain circuit is only capable of producing 150 psi before case flow is choked off. As a result, case drain flow through a filter element is gradually reduced until the element is 2/3 plugged and all case flow is recirculated back to the inlet, which is harmful to the pump and causes the system to operate hot. Consequently, pumps may operate for long periods with dirty filters and little if any case flow while only popping indicators after pump internals are damaged and pump case flow (internal leakage) increases.

F/A-18C/D pressure and return delta P indicators have 18 in. of capillary tube to filter pressure spikes and eliminate nuisance filter replacements. Analysis of filter elements replaced after 200 hr shows the current indicators do not adequately identify dirty elements. Filter elements must produce sustained excessive pressures for more than 3 min before the indicators release. Since large demands are relatively short in duration, this indicator only identifies the most severely clogged filters. As a result, systems operate with loaded filters and high fluid temperatures.

Several years ago, the program identified a manifold checkvalve in the case drain line that was prone to clogging and sticking shut. Removal of this checkvalve and the 200 hr filter change requirement has steadily increased pump life over the past few years.

Filter elements from smaller HS-1 flight control systems load faster than those from HS-2 larger combined (flight controls and utility systems) hydraulic systems. F/A-18C/D field activities report twice as many filter removals for HS-1 as HS-2. Maintenance data also show higher numbers of failed pumps, reservoirs, and other components from HS-1 vice HS-2. This is likely due to higher fluid temperatures for the HS-1 system.

A 200 hr case drain filter was ultrasonically washed with PD-680 to remove any material mechanically lodged in filter fibers. The cleaned filter (figure A-2) shows large amounts of dark organic gel still clogging most of the fluid passages through the media.

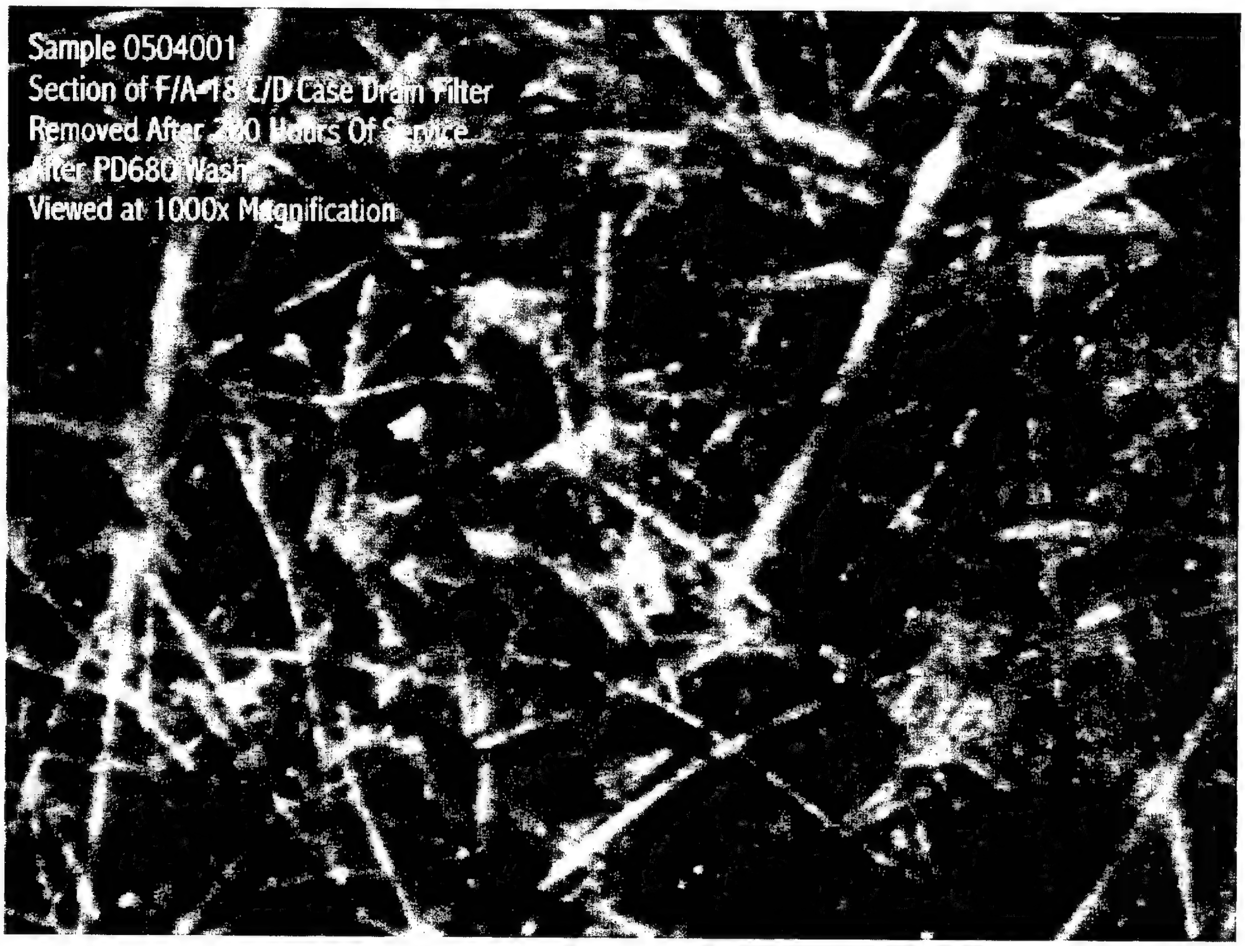


**Figure A-2: F/A-18C/D Filter Removed After 200 hr**

Inspection of failed and ruptured hydraulic pumps shows indications of restricted case drain flow. A 2300 hr forced removal for pumps was imposed to guard against in-flight pump fires. Pressure and return filter elements were life limited to 400 hr and case drain filters were limited

to 200 hr in an effort to reduce system back pressure. The filter service limits improved reliability and currently all filters are limited to 200 flight-hours. Inspection of several filters removed at 200 hr shows significant pressure drop, which indicates filters may be clogged before 200 hr of service. F/A-18 hydraulic pump service life has been averaging 1200 hr.

For the past several years, the F/A-18C/D community has experienced problems with green filter patches. The material, primarily organic, can be strained out on 0.5 micron patches but has no visible particle size at 1000x magnification. Analysis of a green patch showed the material to be made of 50% carbon and 50% oxygen. During the same time period, bronze cylinder bores for the leading edge flap drive motor started to show increased wear. A typical failed motor shows severe wear of rotor bores and piston shoes, which may be causing elevated internal temperatures and stressing system fluid.

## U.S. NAVY EXPERIENCE WITH F/A-18E/F SUPER HORNET HYDRAULIC SYSTEM

The F/A-18E/F was developed from the F/A-18C/D. Both aircraft have similar hydraulic systems and the original aircraft had 56 gpm pumps with 1 1/4 in. inlet line for a maximum inlet velocity of 19 ft/sec.

All hydraulic system filters on test aircraft E1 were replaced after 90 hr of flight due to unexplained black colored fluid in the filter bowls. Other aircraft operated more than 200 hr on the original hydraulic system filters.

Early performance testing showed the original 56 gpm pump was not sufficient for flight demands and a larger 78 gpm pump was developed. Although qualification testing for the larger hydraulic pump endurance testing was performed with a full flow 1 1/2 in. commercial hose, the larger 78 gpm pump used the same 1 1/4 in. aircraft inlet line for a maximum inlet velocity of 27 ft/sec.

Restricting the pump inlet causes transient inlet cavitation, increased stress on the fluid, and may reduce long-term component reliability. The larger pump increased hydraulic system fluid temperatures by 20 to 30°F.

Shortly after introduction of the larger pump, filters started to fail at 70 hr. Filters continued to clog at ever increasing rates until some filters were clogged at 20 flight-hours. Problems with filter clogging were worse on HS-1 vice HS-2 due to higher fluid temperatures. The case drain filter element clogging was most severe due to high fluid temperatures and small filter elements.

During this same time period, the leading edge flap HDU motors started to experience premature wearout. Each new motor failed earlier and earlier in service. The wear rate on HS-1 motors was twice that of wear on HS-2 motors. Analysis of clogged filters identified most of the material as an insoluble organic gel (shown in figure A-3). While the HDU motors were wearing out at a rapid rate, the amount of bronze material in the typical clogged filter was minimal.

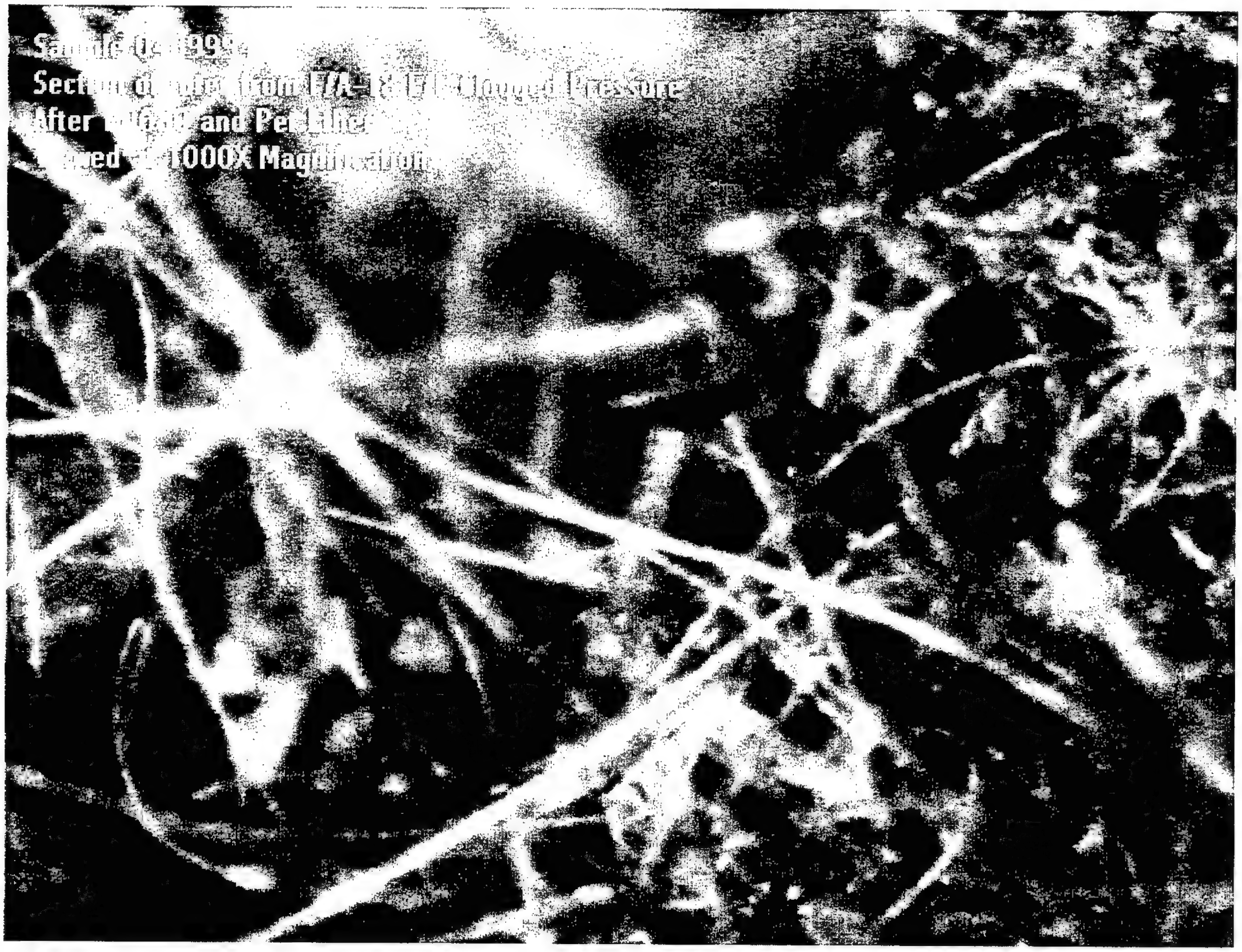

**Figure A-3: F/A-18E/F Clogged Filter After Wash**

Fluid samples taken from aircraft systems with severe wear rates showed reduced levels of barium remaining in the fluid. By contrast, systems with little if any wear problem showed the highest barium levels in the fluid. This is consistent with breakdown of preservative fluid in systems causing filter clogging and component wear.

Testing with a redesigned HDU motor has resolved the premature wearout problems. Analysis of filter elements from one aircraft shows the new motor has also reduced the fluid breakdown problem as well. Filters that were changed every 30 hr are now in service well beyond 400 hr.

Inspection of filter elements removed after 59 hr of service (figure A-4) show buildup of an insoluble red organic material similar to F-14 system filters. Most fluid passages are open and filter service life has improved dramatically. The plaque buildup rate has been significantly reduced but fluid breakdown is still occurring.

Note: All filter elements inspected prior to the HDU motor redesign had dark green organic material, while current filter elements show buildup of red organic material, similar to material collecting on F-14 hydraulic system filters.

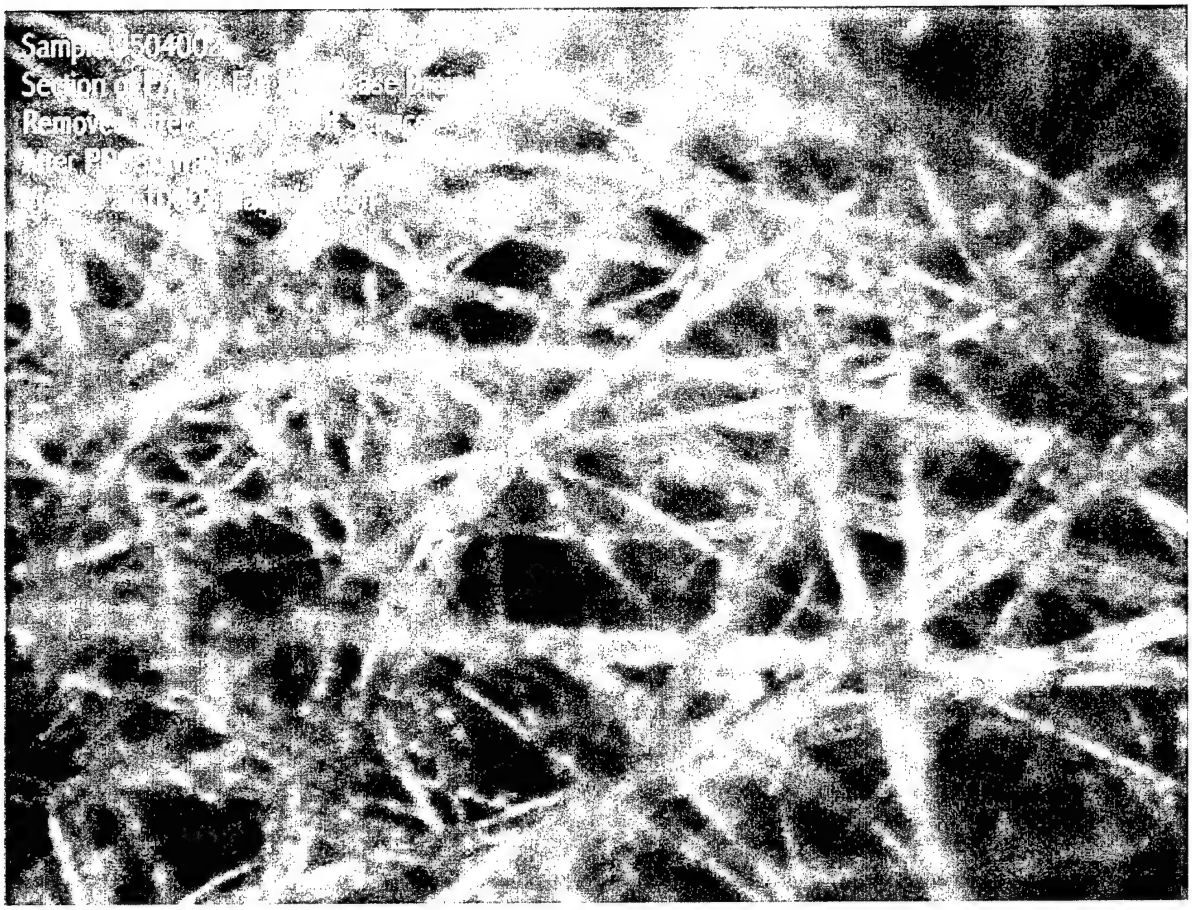

**Figure A-4: F/A-18E/F Case Drain Filter With Improved HDU Motor**

## FOREIGN MILITARY EXPERIENCE WITH AIRCRAFT HYDRAULIC SYSTEMS

Several countries own and operate aircraft manufactured in the U.S. For years, foreign military units have reported component reliability greater than that of U.S. military squadrons. Foreign military countries as a group do not use preservative fluid and have not adopted MIL-H-6083 or MIL-PRF-46170 for storage of components.

New components may contain preservative fluid when shipped from the Original Equipment Manufacturer, but any repair or overhaul is performed with hydraulic fluid. If thermal breakdown of preservative fluid is harming system components, the reduced levels of preservative additive in foreign military hydraulic systems may partially explain the improved service life experienced.

## U.S. NAVY EXPERIENCE WITH V-22 OSPREY HYDRAULIC SYSTEM

The V-22 program did not specify preservative fluid due to the short duration of the EMD phase of testing. System filters are the same 5 micron elements used on F-14 and F/A-18 aircraft and are replaced on condition. One element on one aircraft was clogged at 200 hr while all other

elements are still in service with well over 400 flight-hours. The filter was checked to verify excessive pressure drop and identify filter debris. Most of the material was wear debris and system contaminants.

Washing the media with PD-680 removed the bulk of the material, resulting in clean light gray fibers (figure A-5). Fibers were straight and uniform with no evidence of filter plaque.

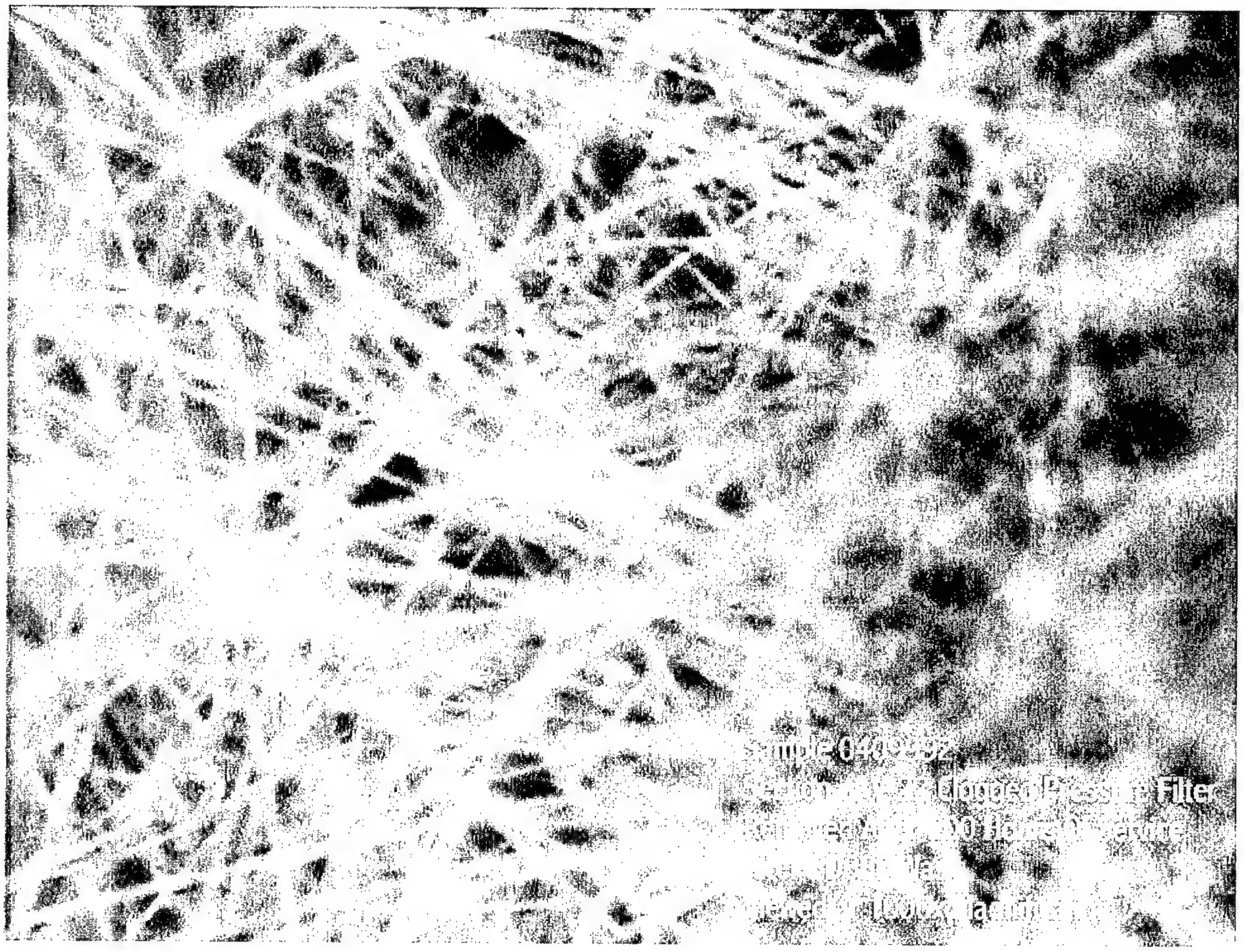

**Figure A-5: V-22 Clogged Filter After Wash**

Due to the short duration of the EMD program, Boeing decided not to require preservative fluid in system components. Although not required, some vendors provided components with preservative fluid, but fluid samples taken have shown V-22 systems as relatively "preservative free". Early in system design, engineers were generous with system cooling and the V-22 operates much cooler than other systems with maximum hydraulic fluid temperatures of approximately 180°F.

Due to problems with other programs compared with excellent V-22 filter service life, the V-22 program has decided not to introduce preservative fluid, as earlier planned.

## COMMERCIAL AIRCRAFT FILTER CLOGGING AND COPPER CHELATE

The standby generator for Boeing 777 aircraft uses a constant speed integrated drive unit with MIL-PRF-23699 (a synthetic oil) as the working fluid. Customers experienced premature filter clogging that was much worse on brand new units. Analysis of clogged filters showed an insoluble green organic gel that required a polar solvent to remove. The material was identified as copper chelate, a single atom of copper surrounded by hydrocarbon rings and long hydrocarbon chains.

MIL-PRF-23699 includes a passivator additive intended to leave the fluid and bind with active metal surfaces and form a barrier between fluid and active metal surfaces to protect fluid and system components from oxidation related damage. The severe operating conditions inside the generator drive unit were damaging the sensitive passivator additive, forming acids, eating away at internal surfaces, and loading system filters with a corrosion byproduct, copper chelate, which is an insoluble green organic gel. The filter vendor developed a material that has helped protect the sensitive passivator additive from in-service breakdown.

The materials and fluids within commercial aircraft motor generators are identical to those used in military aircraft motor generators and accessory gearbox drive units. The commercial aircraft experience directly relates to reliability problems experienced with military aircraft system components.

## U.S. NAVY EXPERIENCE WITH ELECTRIC GENERATOR DRIVE UNITS

Filter elements from CSD units for generators from EA-6 and S-3 aircraft (figure A-6) show insoluble green organic material very similar to the material formed in Boeing 777 generator integrated drive units. It is reasonable to suspect that, as with Boeing 777 generators, this mechanism is leading to premature in-service failures of generator drive units.

There are several sources and types of MIL-PRF-23699 fluids available, if premature service life is a problem, an alternate vendor (with a different additive package) or selection of a severe duty version of MIL-PRF-23699 may help improve reliability. Any equipment using MIL-PRF-23699 may potentially suffer from this mechanism. Further investigation of this type is beyond the scope of this effort.

**Figure A-6: S-3 Aircraft Generator CSD Clogged Filter After Wash**

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| ASN RD&A (PEO(T) (PMA-261)), Bldg. 2272, Room 149<br>47123 Buse Road, Patuxent River, MD 20670-1547 | (1) |
| ASN RD&A (PEO(T) (PMA-265)), Bldg. 2272, Room 445<br>47123 Buse Road, Patuxent River, MD 20670-1547 | (1) |
| ASN RD&A (PEO(T) (PMA-273)), Bldg. 2272, Room 154<br>47123 Buse Road, Patuxent River, MD 20670-1547 | (1) |
| ASN RD&A (PEO(T) (PMA-275)), Bldg. 2272, Room 151<br>47123 Buse Road, Patuxent River, MD 20670-1547 | (1) |
| ASN RD&A (PEO(T) (PMA-276)), Bldg. 2272, Room 150<br>47123 Buse Road, Patuxent River, MD 20670-1547 | (1) |
| ASN RD&A (PEO(T) (PMA-290)), Bldg. 2272, Room 146<br>47123 Buse Road, Patuxent River, MD 20670-1547 | (1) |
| ASN RD&A (PEO(T) (PMA-299)), Bldg. 2272, Room 156<br>47123 Buse Road, Patuxent River, MD 20670-1547 | (1) |
| NAVAVNDEPOT (4.3.4)<br>PSD, Box 8021, Cherry Point, NC 28533-0021 | (1) |

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|---|---|
| NAVAVNDEPOT (4.3.5)<br>PSD, Box 8021, Cherry Point, NC 28533-0021 | (1) |
| NAVAVNDEPOT (4.3.4)<br>NAS, Jacksonville, FL 32212 | (1) |
| NAVAVNDEPOT (4.3.5)<br>NAS, Jacksonville, FL 32212 | (1) |
| NAVAVNDEPOT (4.3.4), Bldg. 469<br>NAS North Island, San Diego, CA 92135-7058 | (1) |
| NAVAVNDEPOT (4.3.5), Bldg. 469<br>NAS North Island, San Diego, CA 92135-7058 | (1) |
| NAVAIRWARCENACDIV (4.8.2.5)<br>Lakehurst, NJ 08733-5000 | (1) |
| DCM Boeing, Mail Stop S2704410, P.O. Box 516<br>5775 Campus Parkway, St. Louis, MO 63166-0516 | (1) |
| NAVTESTWINGLANT (55TW01A) Bldg. 304, Room 200<br>22541 Millstone Road, Patuxent River, MD 20670-1606 | (1) |
| NAVAIRWARCENACDIV (7.2.5.1), Bldg. 405, Room 108<br>22133 Arnold Circle, Patuxent River, MD 20670-1551 | (1) |
| DTIC<br>8725 John J. Kingman Road, Suite 0944, Ft. Belvoir, VA 22060-6218 | (1) |